Plant Archives Vol. 26, Supplement 2, 2026 pp. 2415-2426 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-2.304

EFFECT OF CROP ESTABLISHMENT METHODS AND RESIDUE RETENTION ON GROWTH, YIELD AND ECONOMICS OF *KHARIF* MAIZE (*Zea mays* L.) UNDER CONSERVATION AGRICULTURE

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(Date of Receiving : 16-04-2026; Date of Revision : 04-06-2026; Date of Acceptance : 29-06-2026)

ABSTRACT

A field experiment was conducted to evaluate the impact of different crop establishment methods and residue retention on the productivity and economics of maize (*Zea mays* L.) under conservation agriculture. The study compared zero tillage (ZT) and conventional tillage (CT) systems using drill and dibbling sowing techniques on flat and raised beds, with and without wheat residue retention. Results revealed that ZT-drill sowing with residue consistently outperformed other treatments in terms of plant height, leaf area index, dry matter accumulation and yield attributes. This treatment recorded the highest grain yield (71.3 q/ha), attributed to improved soil moisture conservation, moderated temperature, better plant stand and enhanced yield components such as grains per cob and 100-grain weight. Stover yield was also highest under ZT-drill with residue (89.8 q/ha), due to improved biomass accumulation from better nutrient uptake and reduced weed competition. Biological yield, a sum of grain and stover, reached a maximum of 161.1 q/ha under the same treatment. Harvest index was significantly influenced by establishment methods, with ZT-drill with residue achieving the highest value (44.3%), indicating efficient biomass partitioning to grain. Although shelling percentage was not significantly affected, the highest numerical value (82.2%) was also observed in the ZT-drill with residue treatment. Economic analysis revealed that ZT-drill with residue was the most profitable method, recording the highest gross returns (Rs 1,26,767/ha), net returns (Rs 57,848/ha) and benefit-cost ratio (1.84). Residue retention consistently improved economic returns across all methods by enhancing yields and reducing production costs. Overall, ZT-drill sowing with residue retention emerged as the most effective and sustainable practice, offering higher productivity, better economic returns and improved resource use efficiency. It represents a promising alternative to conventional tillage for enhancing maize performance under conservation agriculture systems.

***Keywords* :** Maize, zero tillage, residue retention, biological yield and harvest index.

Introduction

Maize (*Zea mays* L) is one of the pulsating food grain crops grown under diverse agro-climatic conditions. As it has yield potential far higher than any other cereal, it is sometimes referred as the 'Miracle crop' or the 'Queen of Cereals' (Anjum *et al*., 2014). It is one of the most flexible cereal crops having wider adaptability under various soil and climatic conditions. About 50 maize species exist with variation in colour, texture, grain shape and size and it is cultivated in more than 150 countries throughout the world. Maize is a dual-purpose crop grown for grain as well as fodder. In India, it is 3rd important cereal crop after rice and wheat and cultivated throughout the year viz. *kharif*, *rabi* and spring seasons. The consumption pattern for maize produced in India at present includes poultry feed (52%), human food (24%), animal feed (11%), starch (11%), brewery (1%) and seed (1%) (Dass *et al*., 2007). The increase in demand of maize will continue for the food and feed requirements and will cross the demand of rice as well as wheat (Dixon *et al*., 2009). The renowned Nobel Laureate Dr. Norman E. Borlaug said that "The last two decades saw the revolution in rice and wheat, the next few decades will be known for maize era". Maize is mainly a rainy season i.e. *kharif* crop constitutes 85% of total maize area in the country and contributes 5% to world's dietary energy supply and almost 9% to India's food basket (Yakadri *et al*., 2015). Rice-wheat has become the predominant cropping system after green revolution in north-western India mainly in Indo-Gangetic Plains (IGP) and it has provided food security to the country. But, over exploitation of natural resources like soil and water has resulted in many second-generation problems of land degradation, declining underground water table, environmental pollution, higher production costs and decrease in total factor productivity in rice-wheat cropping system (Jat *et al*., 2013). Maize is the best viable option for the crop diversification in rice-wheat system. Interventions in the form of resource conservation technologies (RCTs) like zero-tillage and furrow irrigated raised bed system (FIRBS) coupled with crop diversification by including maize in place of rice may be an alternate solution which will also improve the soil organic matter content and soil physical properties like soil water holding capacity, porosity and reduces the soil compaction and will promote sustainable cropping systems in the Indo-Gangetic Plains (Jat *et al*., 2007). Crop residue retention is a key component of sustainable cropping systems which improve soil quality, nutrient capacity and reduces the adverse effects of residue burning (Kong, 2014). Hence, there is need to standardize the most suitable establishment methods along with residue retention and their effect on productivity and economics of maize during *Kharif* season.

Materials and Methods

A field experiment was conducted during *Kharif* 2018 at the Regional Research Station, Uchani, Karnal, under CCS Haryana Agricultural University, Hisar (Haryana, India), to assess the impact of various maize establishment methods under residue retention on soil properties and economic returns. Figure 1 illustrates the average weekly weather data recorded during the cropping period. The experimental soil was clay loam in texture, slightly alkaline in reaction (pH 8.1), with an electrical conductivity of 0.30 dS/m. The soil was low in organic carbon (0.40%) and available nitrogen (126 kg/ha), while medium in available phosphorus (16 kg/ha) and potassium (226 kg/ha). The trial was laid out in a randomized block design (RBD) with three replications and eight establishment treatments: zero tillage-drill sown with residue (ZTDS+R), zero tillage-drill sown without residue (ZTDS-R), zero tillage-dibbling with residue (ZTDB+R), zero tillage-dibbling without residue (ZTDB-R), conventional tillage-drill sown (CTDS), conventional tillage-dibbling (CTDB), conventional tillage-raised bed, multi-crop planter (MCP) sown (CTRBDS) and conventional tillage-raised bed, dibbling (CTRBDB). Following the harvest of the preceding *rabi* wheat crop in April, the hybrid maize cultivar HM-10 was sown on July 2, 2018, using a seed rate of 20 kg/ha. Raised beds were prepared using a single pass of a bed planter, followed by sowing via multi-crop planter or manual dibbling depending on the treatment. One row per bed (75 cm wide) was maintained. In conventional tillage treatments, sowing was carried out using a seed drill or manual dibbling at a spacing of 75 × 20 cm. Zero tillage treatments were sown with a zero-till seed drill or by manual dibbling, also maintaining a 75 × 20 cm row spacing. A pre-emergence herbicide, atrazine, was applied at 0.75 kg/ha on July 3, 2018, using a knapsack sprayer equipped with flat-fan nozzles, delivering 500 L/ha spray volume. Crop growth parameters were recorded at 20, 40, 60 DAS and at maturity. Plant population was counted per metre row at 20 DAS and maturity. Plant height was measured from the base to the top leaf or flag leaf collar, depending on growth stage. Leaf area index was calculated using leaf samples from five random plants per plot. Dry matter was assessed by oven-drying plants from two random spots per plot at 70°C to constant weight and expressed in g/m^2. To ensure uniform plant population, manual thinning and gap filling were performed at 20 days after sowing (DAS) as needed. The numbers of cobs per metre row length (mrl) were recorded in each plot at physiological maturity. The length and girth of cob was measured after the harvesting of crop. After harvesting cobs were dried in sunlight and cob weight was recorded by electronic machine. For this purpose, five cobs were randomly selected from each plot. Grain number per cob was recorded at the time of harvesting. Two samples of 100-grains were randomly counted from the sample of net plot yield for each treatment. Average weight was recorded by electronic weighing machine and expressed in grams (g) as 100-grains weight. Harvesting of maize was done manually on October 7, 2018.

Results and Discussion

Growth parameters of maize

Number of plants per metre row length

The number of plants per metre row length in maize, recorded at both 20 days after sowing (DAS) and at crop maturity, was not significantly affected by different crop establishment methods (Table 1). This uniformity across treatments can be attributed to the use of high-quality seed, adequate soil moisture at sowing, adoption of sound agronomic practices and effective gap filling during early crop stages. These factors likely minimized variability in plant stand, regardless of the planting method employed. Similar findings were reported by Awasthi (2014), who also observed no significant differences in plant population per metre row length across various planting methods, emphasizing the importance of good crop management in ensuring uniform plant stands across tillage systems.

Plant height (cm)

Plant height of maize was significantly influenced by different crop establishment methods at various growth stages, namely at 20, 40, 60 days after sowing (DAS) and at maturity (Table 2). Overall, maize grown under zero tillage exhibited taller plants (ranging from 24.6 to 221.0 cm across stages) compared to those under conventional tillage (22.4–203.6 cm). Among zero tillage treatments, drill sowing with wheat residue consistently produced the tallest plants at all stages (28.7, 129.5, 214.1 and 221.0 cm), while the shortest plants were observed in CT-raised bed dibbling (22.4, 103.0, 190.9 and 196.7 cm). At 20 DAS, plant height was significantly greater in ZT-drill (with or without residue) and ZT-dibbling with residue than in CT methods like drill or dibbling on flat and raised beds. ZT-dibbling without residue, though slightly shorter, was statistically comparable to conventional methods. As the crop advanced to 40, 60 DAS and maturity, ZT-drill and dibbling (particularly with residue) maintained significantly greater plant heights than all CT methods. Within the zero-tillage system, drill sowing and dibbling resulted in comparable heights under similar residue conditions. Notably, plant height was consistently higher under residue retention (27.7–221.0 cm) compared to no residue retention (24.6–212.0 cm), though the difference was not always statistically significant. These observations align with earlier studies that attribute enhanced plant growth under zero tillage to improved microclimatic conditions, including optimal soil moisture, better soil structure and reduced compaction, which collectively encourage robust root growth and shoot elongation (Awasthi, 2014; Tiwari, 2016). Zero tillage systems have also been associated with enhanced light interception, improved photosynthetic efficiency and better aeration conditions that foster meristematic activity, cell expansion and overall vegetative vigour (Zhang *et al*., 2007). Enhanced plant height under ZTFS over raised bed and conventional systems was also supported by the findings of Jat *et al*. (2007), Singh *et al*. (2009) and Awasthi (2014). Further physiological advantages under zero tillage include earlier seedling emergence (Srivastava *et al*., 2005), deeper root penetration (Singh *et al*., 2007), moderated soil temperature during initial stages (Jat, 2015) and more efficient nutrient uptake all contributing to enhanced vegetative growth. Khedwal *et al*. (2018) also emphasized the role of residue retention in promoting taller plants under zero tillage, possibly due to better moisture conservation and weed suppression. Similarly, the positive impact of surface mulching on plant height has been corroborated by several studies (Khurshid *et al*., 2006; Singh and Vashist, 2015; Singh *et al*., 2015; Singh *et al*., 2016; Jakhar *et al*., 2017). While many findings support the superiority of zero tillage, some studies reported comparable plant height under both ZT and CT systems (Ram *et al*., 2010). Ramesh *et al*. (2016) noted that while emergence was better with manual seed drills, taller plants were recorded with multi-crop planters, underscoring the role of equipment in influencing crop vigour across systems.

Leaf area index

Leaf area index (LAI) of maize, recorded at 20, 40, 60 DAS and at maturity, was significantly influenced by various crop establishment methods (Table 3). Across all treatments, LAI increased progressively up to 60 DAS, followed by a decline at maturity, likely due to senescence and drying of older leaves. Among the establishment methods, higher LAI values were observed under zero tillage (0.58–6.70) as compared to conventional tillage (0.46–5.68), though the differences were not always statistically significant. At the early stage of 20 DAS, ZT-drill and ZT-dibbling with wheat residue recorded significantly higher LAI compared to CT-drill and CT-dibbling methods on both flat and raised beds. In contrast, ZT treatments without residue were comparable to CT methods. At later stages (40 and 60 DAS and maturity), ZT-drill sown (with or without residue) and ZT-dibbling with residue consistently produced significantly higher LAI than all conventional methods. ZT with residue retention showed superior LAI values (0.63–6.70) compared to ZT without residue (0.58–6.20), particularly from 40 DAS onward. Within zero tillage, drill sowing (with or without residue) resulted in numerically higher LAI than dibbling, but the difference was not always significant. The maximum LAI was observed under ZT-drill sowing with wheat residue (0.67, 5.59, 6.70 and 5.39 at 20, 40, 60 DAS and maturity respectively), whereas the lowest values were recorded under CT-raised bed dibbling (0.46, 4.16, 5.00 and 4.36 at respective stages). In conventional tillage, CT-flat bed dibbling (0.54–5.68) outperformed CT-raised bed dibbling (0.46–5.00), especially at early and mid-growth stages. Similarly, in CT-raised bed method, multi-crop planter (MCP) sowing produced significantly higher LAI than dibbling at 60 DAS and maturity. Under CT-flat bed, LAI was slightly higher in dibbling (0.54–5.68) than drill sowing (0.49–5.19), though differences were not always statistically significant. Higher LAI under zero tillage, especially with residue retention, may be attributed to improved microclimate, enhanced soil moisture availability, reduced weed competition and better crop growth dynamics conditions favourable for increased leaf expansion and photosynthetic surface development. These findings are consistent with those reported by Bakht *et al*. (2006), Jat *et al*. (2006), Avatar *et al*. (2010) and Awasthi (2014), who also noted superior LAI under ZT followed by furrow irrigated raised bed systems (FIRBS) and CT in maize. Likewise, Tiwari (2016) observed higher LAI under ZT and raised beds over conventional flat and minimum till systems. Khedwal *et al*. (2018) also reported enhanced LAI under ZT with residue retention compared to other tillage methods. Moreover, Ram (2006) concluded that permanent beds with retained residues exhibited higher LAI than no-residue conditions under both ZT and CT. However, some studies, such as Ram *et al*. (2010), found no statistically significant difference in LAI across tillage systems, indicating that other agronomic factors might also play a role. The higher LAI values under residue retention (0.63–6.70) as opposed to without residue (0.58–6.20) further emphasize the importance of mulch in modifying soil-plant interactions. Residue mulch likely enhanced moisture conservation, reduced weed pressure and improved overall crop microenvironment. These observations align with previous findings on the benefits of mulching by Ram (2006), Choudhary and Kumar (2014), Singh and Vashist (2015), Singh *et al*. (2015), Jakhar *et al*. (2017) and Khedwal *et al*. (2018), all of whom reported a positive effect of mulching on LAI development.

Plant dry matter accumulation (g/m^2)

Dry matter accumulation in maize at different growth stages (20, 40, 60 DAS and at maturity) was significantly influenced by crop establishment methods (Table 4). Across all stages, zero tillage (ZT) treatments consistently exhibited higher dry matter accumulation (49.5–1637.7 g/m^2) compared to conventional tillage (CT) methods (40.2–1476.4 g/m^2), though differences were not always statistically significant. At 20 DAS, ZT-drill sowing and dibbling with wheat residue resulted in significantly greater dry matter accumulation than their CT counterparts. ZT treatments without residue showed values statistically at par with CT methods. From 40 DAS onwards, ZT-drill sowing with residue produced significantly higher dry matter accumulation than all CT treatments. At maturity, both ZT-drill and ZT-dibbling (with or without residue) outperformed CT methods. ZT-drill sowing with residue emerged as the most effective treatment, recording the highest dry matter accumulation at all stages (57.2, 475.0, 975.3 and 1637.7 g/m^2 at 20, 40, 60 DAS and maturity, respectively). In contrast, the lowest values were observed under CT raised bed-dibbling (40.2, 410.7, 879.5 and 1426.9 g/m^2 at respective stages). ZT with residue retention (54.7–1637.7 g/m^2) consistently resulted in greater biomass than ZT without residue (49.5–1542.5 g/m^2), indicating the positive role of residue mulch in enhancing plant growth conditions. Within ZT, drill sowing (51.3–1637.7 g/m^2) and dibbling (49.5–1603.2 g/m^2) showed statistically similar results. Among CT methods, dry matter accumulation under flat bed-drill and raised bed-MCP sowing was comparable, though MCP sowing on raised beds yielded significantly higher biomass at maturity. Dibbling on CT flat beds (47.1–1476.4 g/m^2) was significantly superior to CT raised bed-dibbling (40.2–1426.9 g/m^2). Similarly, dibbling was more effective than drill sowing under CT-flat bed at maturity, while MCP sowing outperformed dibbling under CT-raised beds at 20 DAS and maturity. The improved performance of ZT treatments, particularly with residue retention, may be attributed to enhanced microclimatic conditions, better soil moisture availability, reduced weed competition and greater photosynthetic efficiency. This corresponds with improvements in plant height and LAI under similar treatments, as previously discussed. Enhanced soil structure and fertility under ZT especially with surface residue retention facilitated better nutrient availability, root proliferation and efficient water utilization, contributing to greater biomass production. These findings are supported by earlier studies (Jat *et al*., 2006; Avatar *et al*., 2010; Hussain *et al*., 2010; Gul *et al*., 2015), which reported superior dry matter accumulation under ZT compared to conventional systems. Mechanisms contributing to this include improved light interception (Tisdale *et al*., 1985), higher nutrient uptake (Yadav *et al*., 2002; Walker *et al*., 2003) and moderated soil temperature and moisture regimes (Yadav *et al*., 2005; Awasthi, 2014; Jat, 2015). According to Harikrishna *et al*. (2005) and Khedwal *et al*. (2018), flat sowing under zero tillage outperformed other tillage forms in total biomass production. However, Ram *et al*. (2010) observed statistically similar dry matter accumulation under different tillage methods in certain conditions. Residue retention played a pivotal role in enhancing biomass accumulation (1637.7 vs. 1542.5 g/m^2 under ZT). This may be due to better conservation of soil moisture, reduced weed interference and improved micro-environment for plant growth. These benefits of mulching are well documented by Khurshid *et al*. (2006), Singh and Vashist (2015), Singh *et al*. (2016), Jakhar *et al*. (2017) and Khedwal *et al*. (2018).

Yield attributing parameters of maize

Number of cobs per metre row length

Different crop establishment methods had no statistically significant effect on the number of cobs per metre row length, as nearly uniform values were recorded across all treatments (Table 5). Residue retention also did not notably influence this trait compared to treatments without residue. However, the numerically highest value (5.2 cobs/metre) was observed under zero tillage with drill sowing and wheat residue, while the lowest (4.7 cobs/metre) was under conventional tillage on raised beds with dibbling. These slight numerical advantages in zero tillage systems may reflect improved micro-environmental conditions that enhance stand establishment and early growth, consistent with the findings of Bakht *et al*. (2006) and Singh *et al*. (2009), who reported higher cob numbers under ridge planting, although not always significantly different from other methods. Raihan *et al*. (2017) similarly found no significant effect of establishment method on number of cobs per plant.

Cob length (cm)

Cob length in maize was not significantly influenced by establishment methods (Table 5). However, maize under zero tillage exhibited numerically longer cobs (17.2–18.1 cm) compared to conventional tillage (14.6–16.9 cm). Residue retention had little effect in improving cob length over residue-free treatments. Within the zero-tillage category, both drill and dibbling methods (with or without residue) gave similar results. Among conventional tillage systems, comparable cob lengths were observed across methods, with the shortest recorded under raised bed-dibbling (14.6 cm) and the longest in zero tillage drill sowing with wheat residue (18.1 cm). The superior cob length in zero tillage may be attributed to enhanced soil structure and reduced mechanical impedance, leading to better root growth and nutrient uptake (Idnani and Kumar, 2012). These observations align with Khedwal *et al*. (2017), who reported longer cobs under zero tillage with residue retention. Conversely, Yadav *et al*. (2015) noted significantly higher cob length in ridge planting, suggesting that the response may vary by site and soil type.

Cob girth (cm)

The girth of maize cobs was not significantly altered by different establishment methods (Table 5). Residue retention, similarly, did not yield a noticeable improvement. All treatments resulted in statistically similar girths, although the thickest cobs (13.3 cm) were produced under zero tillage drill sowing with wheat residue and the thinnest (12.0 cm) under conventional raised bed-dibbling. These patterns reflect the generally more favourable root and canopy environments under zero tillage, which may facilitate improved translocation of assimilates. Khedwal *et al*. (2017) also reported improved cob girth with zero tillage and residue retention. While Singh *et al*. (2008) found no significant differences in girth, Yadav *et al*. (2015) observed higher girth in ridge planting, showing variability across studies. Cob girth tends to respond to improved plant vigour, which is often better supported in zero till systems due to improved moisture retention and soil aeration.

Cob weight (g)

Cob weight was the only yield parameter that showed a significant response to crop establishment methods (Table 5). Zero tillage methods consistently produced heavier cobs (126.6–132.5 g) compared to conventional tillage methods (120.7–124.8 g). The highest cob weight (132.5 g) was recorded under zero tillage drill sowing with wheat residue, while the lowest (120.7 g) was from conventional raised bed-dibbling. Even within zero tillage, residue retention improved cob weight, with drill sowing with residue outperforming residue-free methods. Cob weight under zero tillage-drill (with residue) was 7.0% and 7.8% higher than under CT-flat bed and CT-raised bed, respectively. These results support findings by Zhang *et al*. (2007), who linked better yield attributes under zero tillage to improved light penetration and photosynthesis. Similarly, Sewhag *et al*. (2010) reported that higher dry matter under zero tillage resulted from increased leaf area index (LAI) and photosynthetic efficiency, leading to more assimilates being translocated to cobs. Yadav *et al*. (2005) also noted better plant establishment, moisture conservation and reduced weed pressure under zero tillage, which collectively contributed to higher cob weight and overall productivity. While Singh *et al*. (2008) and Ram *et al*. (2010) found no statistical differences in cob weight across tillage systems, the current results and others like those from Pradhan *et al*. (2018) highlight that zero tillage with residue retention provides a consistent advantage in improving this key yield attribute.

Number of grains per cob

Number of grains per cob did not show significant differences across establishment methods, although zero tillage treatments showed numerically higher values (408.1–425.3 grains/cob) than conventional tillage (390.7–406.6 grains/cob) (Table 5). Residue retention did not influence the number of grains per cob substantially. All combinations within both zero tillage and conventional tillage systems showed similar results. Nevertheless, the highest grain number (425.3 grains/cob) was from zero tillage drill sowing with wheat residues, while the lowest (390.7 grains/cob) was under CT raised bed-dibbling. The enhanced performance under zero tillage may be explained by improved root development and moisture availability, which sustain reproductive growth and kernel setting. Jat *et al*. (2005) found a significantly higher number of grains per cob under zero tillage, attributing it to better growth conditions and nutrient availability. Pradhan *et al*. (2018) also noted increased grain numbers in zero tillage systems with residue retention. These observations underscore the role of conservation agriculture practices in stabilizing reproductive performance even under varying field conditions.

100-grain weight (g)

The 100-grain weight was not significantly affected by establishment methods (Table 5). Residue retention also did not provide any consistent advantage in this trait. However, zero tillage drill sowing with wheat residue showed the highest numerical test weight (26.9 g), while the lowest (25.4 g) was seen in conventional raised bed-dibbling. These patterns align with the understanding that zero tillage, by improving moisture conservation and reducing stress during grain filling, can enhance kernel development and mass. Khedwal *et al*. (2017) and Pradhan *et al*. (2018) both recorded higher grain weights in zero tillage with residue systems. Yadav *et al*. (2005) emphasized the role of improved crop establishment and moisture dynamics in increasing test weight under zero tillage.

Yield

Grain yield (q/ha)

Grain yield of maize was significantly influenced by different crop establishment methods (Table 6). Zero tillage (ZT) methods, particularly ZT-drill sowing with wheat residue retention, consistently recorded higher grain yields (up to 71.3 q/ha) as compared to conventional tillage (CT) methods (57.0–62.7 q/ha). Among ZT treatments, residue retention contributed notably to yield improvement. While ZT-drill and ZT-dibbling were statistically similar, numerically, drill sowing outperformed dibbling. In the CT treatments, flat bed-dibbling yielded the most (62.7 q/ha), whereas raised bed-dibbling had the lowest yield (57.0 q/ha). The enhanced grain yield under ZT-drill sowing with residue can be attributed to better soil moisture conservation, reduced temperature fluctuations and suppression of weeds due to the mulch effect of retained residues. These factors contribute to an improved soil microclimate that favours maize growth. Moreover, ZT encourages better soil structure and microbial activity due to minimal disturbance, leading to enhanced nutrient availability. Improved plant stand, greater number of grains per cob and heavier 100-grain weight under ZT further contributed to higher grain yields, as supported by findings of Jat *et al*. (2005), Ram *et al*. (2010) and Singh *et al*. (2007).

Stover yield (q/ha)

Stover yield was also significantly affected by different crop establishment methods (Table 6). Zero tillage methods resulted in higher stover yields (83.5–89.8 q/ha) compared to CT methods (77.1–82.3 q/ha). Among these, the highest stover yield was observed under ZT-drill sowing with wheat residue (89.8 q/ha), while ZT-dibbling without residue recorded the lowest (83.5 q/ha) among ZT treatments. ZT-drill sowing (with or without residue) produced higher stover yields than ZT-dibbling, although the difference was not statistically significant. Within CT, stover yields were similar across methods, with the lowest yield under raised bed-dibbling. The increased stover yield under ZT, particularly with residue retention, can be explained by improved plant growth due to enhanced soil moisture and reduced evaporative losses. The mulch layer formed by crop residues reduces weed competition, allowing better nutrient uptake and biomass production. The structural improvement in soil under ZT, such as increased porosity and aggregate stability, enhances root proliferation and nutrient use efficiency, resulting in greater above-ground biomass. Previous studies by Khedwal *et al*. (2017) and Awasthi

(2014) also reported superior stover yields under ZT systems with residue retention.

Biological yield (q/ha)

Biological yield, the sum of grain and stover yields, was significantly influenced by crop establishment methods (Table 6). ZT systems yielded more (147.7–161.1 q/ha) than CT systems (134.1–145.0 q/ha). ZT-drill sowing with wheat residue showed the highest biological yield (161.1 q/ha), while the lowest was recorded under CT raised bed-dibbling (134.1 q/ha). Residue retention consistently improved biological yields compared to no-residue conditions in ZT, although differences between drill and dibbling methods were not statistically significant. Higher biological yield under ZT is largely a function of increased grain and stover yields. The better soil physical conditions under ZT due to less disturbance preserve soil organic matter and structure, which supports root development and nutrient availability. Additionally, residue retention promotes a favourable soil-water balance and minimizes weed pressure, resulting in increased photosynthesis and dry matter accumulation. Enhanced radiation use-efficiency and canopy development in ZT systems further explain the higher biological productivity, as noted by Singh *et al*. (2008), Govaerts *et al*. (2007) and Blackshaw *et al*. (2007).

Harvest Index (%)

Harvest index, representing the ratio of grain yield to biological yield, was significantly affected by the method of crop establishment (Table 6). ZT treatments recorded higher harvest index values (43.5–44.3%) than CT treatments (42.5–43.2%). The highest HI was found in ZT-drill sowing with wheat residue (44.3%), while the lowest was in CT raised bed-dibbling (42.5%). Within ZT, differences among methods were not significant, but residue retention numerically improved HI. The increased harvest index in ZT can be attributed to the favourable conditions for reproductive growth, ensuring a greater proportion of dry matter is allocated to grain production. Under residue-retained conditions, enhanced water availability and moderated temperature stress during the grain-filling stage contribute to better kernel development. This results in more efficient conversion of total biomass into economic yield. These findings are supported by Blackshaw *et al*. (2007), who noted higher harvest indices in conservation tillage systems due to improved partitioning of assimilates to the grain.

Shelling percentage (%)

Unlike other parameters, shelling percentage was not significantly influenced by crop establishment methods (Table 6). However, numerically, ZT-drill sowing with residue recorded the highest shelling percentage (82.2%) and CT raised bed-dibbling recorded the lowest (77.1%). Residue retention had no significant effect on shelling percentage. Since shelling percentage largely depends on kernel development rather than total biomass or tillage effect, it remained relatively unaffected across treatments. Variability observed in numerical terms might be due to slight differences in grain filling, cob size and seed set, which were more influenced by plant genetics and environmental factors during the reproductive phase than by tillage practices (Singh *et al*., 2008).

Economics

Economic data presented in Table 7 indicates that zero tillage (ZT) with drill sowing and wheat residue retention was the most profitable establishment method. This treatment recorded the highest gross returns of Rs 1,26,767/ha, net returns of Rs 57,848/ha and a benefit-cost (B:C) ratio of 1.84. In contrast, the least economic performance was observed under conventional tillage (CT) with raised bed-dibbling, which produced gross returns of Rs 1,02,451/ha, net returns of Rs 30,927/ha and the lowest B:C ratio of 1.43. Residue retention across all treatments led to better economic outcomes. Treatments with residue yielded net returns ranging from Rs 51,717 to Rs 57,848/ha and B:C ratios between 1.73 and 1.84, while those without residue had slightly lower figures, with net returns of Rs 48,033 to Rs 52,282/ha and B:C ratios between 1.72 and 1.81. The ZT-drill sown without residue treatment followed closely in profitability, showing a B:C of 1.81. These economic advantages under ZT can be attributed to reduced production costs due to elimination of ploughing and bed formation, better moisture conservation and lower weed infestation, all of which contributed to higher grain and stover yields. Additionally, ZT allows for timely sowing and efficient use of inputs, which enhances returns. Supporting research (Jat *et al*., 2005; Jat *et al*., 2011; Kumar & Angadi, 2014; Vial *et al*., 2015) has also demonstrated the economic superiority of conservation agriculture (CA) systems over conventional tillage methods. Moreover, studies such as those by Bahar (2013) and Sepat & Rana (2013) confirm that straw or residue mulching significantly improves net returns and B:C ratios compared to non-mulched treatments. The highest cultivation costs were reported for CT-flat and CT-raised beds due to extensive tillage and bed formation, which not only increased expenses but also reduced profitability. Similar trends have been reported by Awasthi (2014), Devi (2015) and Singh *et al*. (2011), all emphasizing that ZT leads to better net returns per rupee invested. ZT-drill sowing with residue retention provides the most economically viable option for maize cultivation. It enhances yield while minimizing input costs, thereby maximizing returns. As a result, it supports not just profitability but also resource conservation, timely crop establishment and long-term sustainability in maize-based farming systems.

Conclusion

The results of this study demonstrate that crop establishment methods significantly influence maize growth, yield and profitability. Among the tested treatments, zero tillage drill sowing with wheat residue retention emerged as the most effective strategy, recording superior performance in growth parameters, grain and stover yields and biological productivity. Residue retention played a pivotal role in enhancing soil physical conditions, conserving moisture, reducing weed competition and ultimately improving nutrient uptake and dry matter partitioning. Economically, ZT-drill sowing with residue yielded the highest net returns and benefit-cost ratio, primarily due to lower production costs and improved yields. In contrast, conventional tillage methods, particularly raised bed-dibbling, were less efficient in both agronomic and economic terms. These findings support the broader adoption of zero tillage and residue-based conservation agriculture for enhancing productivity, profitability and sustainability in maize-based cropping systems.

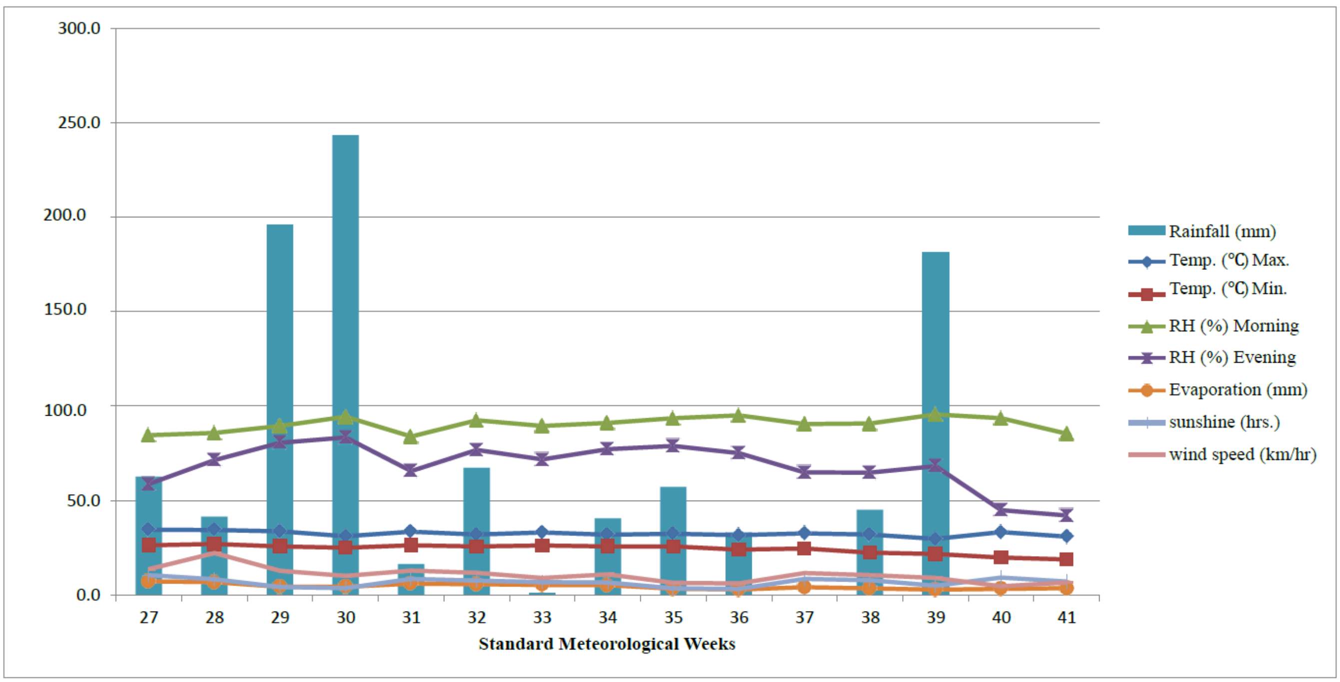

Fig. 1 : Mean weekly meteorological data of crop season

Table 1 : Effect of different methods of establishment on number of plants per metre row length of *Kharif* maize

Treatment	No of plants per metre row length	
	20 DAS	At maturity
ZT-Drill sown (with wheat residues)	5.7	5.2
ZT-Drill sown (without residues)	5.0	5.0
ZT-Dibbling (with wheat residues)	5.3	5.2
ZT-Dibbling (without residues)	5.0	5.0
CT (Flat bed)-Drill sown	5.0	4.8
CT (Flat bed)-Dibbling	5.3	5.0
CT (Raised bed)-MCP sown	5.3	5.0
CT (Raised bed)-Dibbling	5.0	4.7
SEm±	0.2	0.1
CD at 5%	NS	NS

Table 2 : Effect of different methods of establishment on plant height of *Kharif* maize

Treatment	Plant height (cm)			
	20 DAS	40 DAS	60 DAS	At maturity
ZT-Drill sown (with wheat residues)	28.7	129.5	214.1	221.0
ZT-Drill sown (without residues)	26.6	123.1	206.8	212.0
ZT-Dibbling (with wheat residues)	27.7	126.6	209.8	215.8
ZT-Dibbling (without residues)	24.6	119.2	203.8	210.6
CT (Flat bed)-Drill sown	22.5	105.9	194.5	200.7
CT (Flat bed)-Dibbling	23.2	113.7	198.7	203.6
CT (Raised bed)-MCP sown	23.1	109.4	196.4	201.7
CT (Raised bed)-Dibbling	22.4	103.0	190.9	196.7
SEm±	0.9	3.8	3.6	3.6
CD at 5%	2.8	11.7	10.9	10.9

Table 3 : Effect of different methods of establishment on leaf area index (LAI) of *Kharif* maize

Treatments	Leaf area index			
	20 DAS	40 DAS	60 DAS	At maturity
ZT-Drill sown (with wheat residues)	0.67	5.59	6.70	5.39
ZT-Drill sown (without residues)	0.60	4.88	6.20	5.07
ZT-Dibbling (with wheat residues)	0.63	5.33	6.50	5.21
ZT-Dibbling (without residues)	0.58	4.70	6.03	4.96
CT (Flat bed)-Drill sown	0.49	4.26	5.19	4.49
CT (Flat bed)-Dibbling	0.54	4.56	5.68	4.76
CT (Raised bed)-MCP sown	0.52	4.34	5.42	4.64
CT (Raised bed)-Dibbling	0.46	4.16	5.00	4.36
SEm±	0.02	0.08	0.09	0.08
CD at 5%	0.07	0.26	0.28	0.23

Table 4 : Effect of different methods of establishment on dry matter accumulation in *Kharif* maize

Treatment	Dry matter accumulation (g/m^2)			
	20 DAS	40 DAS	60 DAS	At maturity
ZT-Drill sown (with wheat residues)	57.2	475.0	975.3	1637.7
ZT-Drill sown (without residues)	51.3	461.3	952.7	1542.5
ZT-Dibbling (with wheat residues)	54.7	466.8	966.4	1603.2
ZT-Dibbling (without residues)	49.5	447.3	939.6	1520.6
CT (Flat bed)-Drill sown	42.7	420.9	898.0	1439.0
CT (Flat bed)-Dibbling	47.1	442.4	924.6	1476.4
CT (Raised bed)-MCP sown	45.0	431.2	904.3	1464.1
CT (Raised bed)-Dibbling	40.2	410.7	879.5	1426.9
SEm±	1.4	9.7	14.7	7.3
CD at 5%	4.3	29.7	44.9	22.5

Table 5 : Effect of different establishment methods and residue retention on yield attributes

Treatment	No. of cobs /mrl	Cob Length (cm)	Cob Girth (cm)	Cob weight (g)	No. of grains /cob	100-grain weight (g)
ZT-Drill sown (with wheat residues)	5.2	18.1	13.3	132.5	425.3	26.9
ZT-Drill sown (without residues)	5.0	17.2	13.1	128.4	411.9	26.5
ZT-Dibbling (with wheat residues)	5.2	17.6	13.3	130.6	418.6	26.6
ZT-Dibbling (without residues)	5.0	17.2	13.1	126.6	408.1	26.3
CT (Flat bed)-Drill sown	4.8	16.4	12.4	121.7	394.5	25.7
CT (Flat bed)-Dibbling	5.0	16.9	13.0	124.8	406.6	26.1
CT (Raised bed)-MCP sown	5.0	16.3	12.8	123.7	399.4	26.0
CT (Raised bed)-Dibbling	4.7	14.6	12.0	120.7	390.7	25.4
SEm±	0.1	0.6	0.3	2.3	7.9	0.7
CD at 5%	NS	NS	NS	7.0	NS	NS

Table 6 : Effect of different establishment methods and residue retention on yield attributes

Treatment	Grain yield (q/ha)	Stover yield (q/ha)	Biological yield (q/ha)	Harvest index (%)	Shelling (%)
ZT-Drill sown (with wheat residues)	71.3	89.8	161.1	44.3	82.2
ZT-Drill sown (without residues)	65.4	84.6	150.0	43.6	80.1
ZT-Dibbling (with wheat residues)	69.1	88.7	157.8	43.8	80.6
ZT-Dibbling (without residues)	64.2	83.5	147.7	43.5	79.8
CT (Flat bed)-Drill sown	59.2	79.0	138.2	42.9	78.0
CT (Flat bed)-Dibbling	62.7	82.3	145.0	43.2	79.0
CT (Raised bed)-MCP sown	61.4	81.2	142.6	43.1	78.5
CT (Raised bed)-Dibbling	57.0	77.1	134.1	42.5	77.1
SEm±	1.7	2.2	3.8	0.3	1.0
CD at 5%	5.1	6.8	11.7	1.0	NS

Table 7 : Effect of different methods of establishment on economics of *Kharif* maize

Treatments	Cost of cultivation (Rs/ha)	Gross return (Rs/ha)	Net returns (Rs/ha)	B:C Ratio
ZT-Drill sown (with wheat residues)	68,919	1,26,767	57,848	1.84
ZT-Drill sown (without residues)	64,387	1,16,669	52,282	1.81
ZT-Dibbling (with wheat residues)	71,185	1,22,902	51,717	1.73
ZT-Dibbling (without residues)	66,653	1,14,685	48,033	1.72
CT (Flat bed)-Drill sown	68,239	1,06,106	37,867	1.55
CT (Flat bed)-Dibbling	70,505	1,12,050	41,546	1.59
CT (Raised bed)-MCP sown	69,258	1,09,948	40,690	1.59
CT (Raised bed)-Dibbling	71,524	1,02,451	30,927	1.43

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